Chapter 8

Refinement of Protocols for Measuring the Apparent Optical Properties of Seawater

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8.1 INTRODUCTION

Ocean color satellite missions, like the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) or the Moderate Resolution Imaging Spectroradiometer (MODIS) projects, are tasked with acquiring a global ocean color data set, validating and monitoring the accuracy and quality of the data, processing the radiometric data into geophysical units using a set of atmospheric and bio-optical algorithms, and distributing the final products to the scientific community. The long-standing requirement of the SeaWiFS Project, for example, is to produce spectral water-leaving radiances, $L_W(\lambda)$, to within 5% absolute (λ denotes wavelength) and chlorophyll *a* concentrations to within 35% (Hooker and Esaias 1993), and most ocean color sensors have the same or similar requirements. Although a diverse set of activities are required to ensure the accuracy requirements are met (Hooker and McClain 2000), the perspective here is with field observations. Assuming half of the total uncertainty budget is apportioned to the satellite sensor and that the uncertainties sum in quadrature (the square root of the sum of the squares), the allowed uncertainty in the *in situ* data is approximately 3.5% ($\sqrt{5^2/2}$).

The accurate determination of upper ocean apparent optical properties (AOPs) is essential for the vicarious calibration of ocean color data and the validation of the derived data products, because the sea-truth measurements are used to evaluate the satellite observations (Hooker and McClain 2000). The uncertainties with *in situ* AOP measurements have various sources: a) the sampling procedures used in the field, including the environmental conditions encountered; b) the absolute characterization of the radiometers in the laboratory; c) the conversion of the light signals to geophysical units in a processing scheme, and d) the stability of the radiometers in the harsh environment they are subjected to during transport and use. Assuming ideal environmental conditions, so this aspect can be neglected, the SeaWiFS ground-truth uncertainty budget can only be satisfied if each uncertainty is on the order of 1–2%, or what is generally referred to as *1% radiometry*.

In recent years, progress has been made in estimating the magnitude of some of these uncertainties and in defining procedures for minimizing them. For the SeaWiFS Project, the first step was to convene a workshop to draft the SeaWiFS Ocean Optics Protocols (hereafter referred to as the Protocols). The Protocols initially adhered to the Joint Global Ocean Flux Study (JGOFS) sampling procedures (JGOFS 1991) and defined the standards for optical measurements to be used in SeaWiFS calibration and validation activities (Mueller and Austin 1992). Over time, the Protocols were revised (Mueller and Austin 1995), and then recurringly updated on essentially an annual basis (Mueller 2000, 2002, and 2003) as part of the Sensor Inter-comparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) project.

This report summarizes advances in ocean optics protocols derived from a variety of inquiries brought to completion within the last year of the SIMBIOS project. The presentation is restricted to minimizing instrument characterization, *in situ* sampling, and data processing uncertainties for AOP sensors normally used in vicarious calibration activities. The full inquiry included the uncertainties associated with the determination of pigment concentrations using high performance liquid chromatography (HPLC), because pigment concentrations are an essential part of a complete validation program. The results for the latter are not described here, because they are not part of AOP investigations. The complete details, however, are presented in Claustre et al. (2003) and Hooker et al. (2003a).

8.2 INSTRUMENT CHARACTERIZATION PROTOCOLS

The immersion factor, $If\ (\lambda)$, is a necessary part of the spectral characterization of an in-water irradiance sensor, because when a cosine collector is immersed in water, its light transmissivity is less than it was in air. Irradiance sensors are calibrated in air, however, so a correction for this change in collector transmissivity must be applied when the in-water raw data are converted to physical units. The immersion factor must be determined experimentally, using a laboratory protocol, for each collector.

Depth (z) profiles of the downward and upward irradiances, $E_d\ (z,\lambda)$ and $E_u(z,\lambda)$, respectively, are directly influenced by uncertainties in the characterization of immersion factors. Although irradiances do not appear explicitly in the determination of $L_W\ (\lambda)$—which is derived primarily from a profile of the upwelled radiance, $L_u(z,\lambda)$—vicarious calibration activities frequently rely on measurements, normalized variables, or alternative methods for producing $L_W\ (\lambda)$ which require irradiance variables:

1. The Q-factor, which requires $E_u\ (z,\lambda)$ and $L_u\ (z,\lambda)$, or the use of Q-factor look-up tables with measurements of $E_u\ (z,\lambda)$to derive $L_u\ (z,\lambda)$;
2. The irradiance reflectance $R(z,\lambda)$, when computed with $E_u\ (z,\lambda)$ and $E_d\ (z,\lambda)$ obtained from different radiometers;
3. The normalized water-leaving radiance, $L_{WN}\ (\lambda)$, as well as the remote sensing reflectance, $R\mathrm{rs}(\lambda)$, when the solar irradiance, $E_d\ (0^+,\lambda)$, is computed from subsurface $Ed(0^-,\lambda)$values (0^+ and 0^-denote measurements immediately above and below the sea surface, respectively);
4. Determination of the near-surface extrapolation interval, and thus the water-leaving radiance, for those processing schemes taking advantage of the convergence of $E_d\ (0^+,\lambda)$ and $E_d\ (0^-,\lambda)$to select the interval limits; and
5. Derived quantities formed from band ratios of $R\ (\lambda)$, $L_{WN}\ (\lambda)$, or $R\mathrm{rs}(\lambda)$at different wavelengths.

The latter are the input variables for algorithms inverting the optical measurements to derive the chlorophyll *a* concentration (O'Reilly et al. 1998).

Studies of immersion effects date back to the work of Atkins and Poole (1933), who attempted to experimentally estimate the internal and external reflections for an opal glass diffuser. Additional investigations by Berger (1958 and 1961) refined the laboratory procedures and Westlake (1965) gave detailed explanations for the internal and external reflection contributions. A comprehensive description of a protocol for a more modern Plexiglas diffuser was given by Smith (1969). The culmination of these early investigations was the incremental method, or what is now referred to as the *traditional* method.

The traditional method has been in use for the past 25 years, and originated with the protocol revisions suggested by Aas (1969) and communicated more widely by Petzold and Austin (1988). They all advocated using a lamp as a light source and including a geometric correction factor as a function of the lamp–collector distance, incremental changes in the water depth, and the water refractive index. The advantage of the geometric correction factor is it minimizes the effects caused by changes in the flux reaching the collector as a function of the change in water depth.

The traditional method involves a relatively simple procedure and a small number of components (Mueller and Austin 1995). A lamp of suitable wattage is needed to provide a flux of light at all sensor wavelengths well above dark values, with the appropriate baffing and apertures to minimize diffuse light contributions into the tank. A lamp with a small filament is preferred, because it better approximates a point source, and a regulated power supply should be used to ensure the emitted flux from the lamp is stable over the time period of each characterization trial. The water vessel or tank should have a removable aperture sized or adjusted to ensure the direct beam of light from the lamp projects onto an area that is only slightly larger than the area of the diffuser. The interior of the tank must be *flat* black, and contain a sensor support system that permits an accurate horizontal leveling of the diffuser and an accurate alignment of the sensor with respect to the centerline of the lamp filament.

Two alternatives for characterizing immersion factors were recently evaluated by Hooker and Zibordi (2003a). For the first method, the optical measurements taken at discrete water depths are substituted by continuous profiles created by removing the water with a pump. In the second method, the commonly used large tank is replaced bya small water vessel with sidewall baffes, which permits the use of a quality-assured and reproducible volume of water. The latter was achieved by refining the capabilities of the Compact Portable Advanced Characterization Tank (ComPACT), which had already been built for experimenting with immersed sensors.

The continuous method takes advantage of having a pump (with an almost constant discharge rate) to drain the water vessel. For a cylindrical tank, the water depth can be approximated as a linear function of time as the water is pumped out. Consequently, there is no need to stop at discrete depths to record the diffuser measurements. This means the total characterization time is the time needed to prepare, fill, and empty the tank (about 40 min for a large, 350 L, tank), which is considerably shorter than the traditional method (which usually requires about 100 min, but for some setups as much as 300 min).

The ComPACT apparatus originated from a desire to perform quality tests on immersed radiometers either in the field (measuring the response of bio-fouled sensors while still wet) or in the laboratory (the characterization of immersion factors). The original concept was to have a small (portable) water vessel, with baffing elements to minimize light reflections inside the tank if an extended source was used for illumination. The basic elements of the Com-PACT measurement protocol involve many elements associated with the traditional method, e.g, leveling, aligning, and adjusting the components before the experimental process can be executed. These and many other finer levels of detail are not recounted here, because they are provided by Zibordi et al. (2003a). The primary advantages of the ComPACT apparatus in the characterization of immersion factors is a) it only requires 3 L of water, which means pure water, manufactured shortly before use, can be used, and b) the small size places minimal requirements on work spaces and waste water requirements.

The validation of the continuous and ComPACT methodsis accomplished by comparing them to the traditional method. Specifically, the $I_f(\lambda)$values from an alternative method and a specific sensor (Y) are differenced with respect to the $I_f(\lambda)$values for that sensor as provided by the traditional method (X). Relative percent difference (RPD) values,

$$\varphi = 100\frac{Y - X}{X} \tag{8.1}$$

are used to evaluate the performance characteristics of the methods. The overall capabilities are derived by averaging across all sensors or all wavelengths (which are identical for all the sensors).

The intercomparison of the alternative and traditional methods is given in Fig. 8.1. The results show a significant convergence of the two new methods with the traditional method with individual sensor differences generally well below 1%. The histogram of RPD values (inset panel) has a significant central peak, but a slightly distorted gaussian distribution—there is a small net positive bias; the average RPD is 0.1%. The average repeatability for single-sensor characterizations (across seven wavelengths) of the three methods are very similar and approximately 0.5%.

The evaluation of the continuous method demonstrates its full applicability in the determination of immersion factors with a significant time savings. The evaluation of the small water vessel demonstrates the possibility of significantly reducing the size of the tank (along with decreasing Fig. 8.1. A comparison of the traditional $I_f(\lambda)$ method versus the continuous (open circles) and ComPACT (solid circles) methods. The experimental trials for the new methods were executed in as small a time difference with respect to the traditional method as possible. The sensors involved are the same ones characterized during the eighth SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-8) for investigating uncertainties in the traditional method (Zibordi et al. 2003b). The sensors had identical (nominal) center wavelengths and were usually characterized more than once, although one of the radiometers was selected as a so-called *reference* sensor and was measured more frequently than the others. The mix of sensors used with the ComPACT method is different than those used with evaluating the continuous method, but five are common to both and between the two types of experiments, all 12 of the sensors used during SIRREX-8 are represented. The anomalously low *If* (λ)value at approximately 1.275 is a confirmed feature of one of the sensors. The inset panel shows the histogram of RPD values, with the traditional method used as the reference in the RPD calculation.

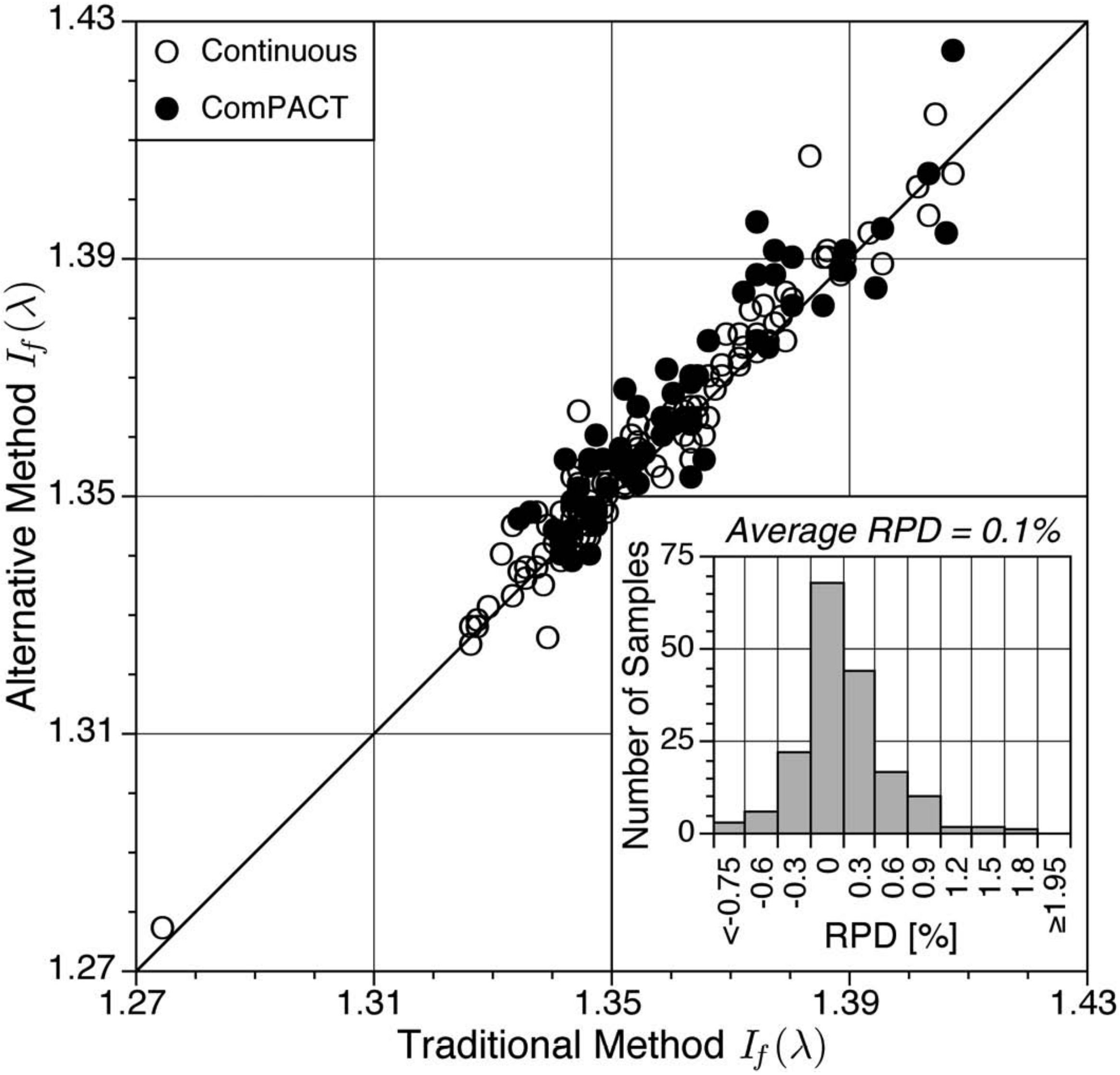

Figure 8.1:A comparison of the traditional I_f (λ) method the continuous (open circles) and ComPACT (solid circles) methods. The experimental trials for the new methods were executed in as small a time difference with respect to the traditional method as possible. The sensors involved are the same ones characterized during the eight SeaWiFS Intercalibration Round Robin Experiments (SIRREX-8) for investigating uncertainties in the traditional method (Zibordi et al. 2003b). The sensors had identical (nominal) center wavelengths and were usually characterized more than once, although one of the radiometers was selected as a so-called *reference* sensor and was measured more frequently than others. The mix of sensors used with the ComPACT method is different than those used with evaluating the continuous method, but five are common to both and between the two types of exeperiments, all 12 of the sensors used during SIRREX-8 are represented. The inset panel shows the histogram of RPD values, with the traditional method used as the reference in the RPD calculation.

the execution time) and permitting a completely reproducible methodology (based on the use of pure water). The results also show sidewall reflections can be properly minimized with internal baffes. Within the context of experimental effciency and reproducibility, this study suggests the combination of a properly baffed small tank with a constant flow pump would be an optimal system.

8.3 IN SITU SAMPLING PROTOCOLS

Achieving working at the 1% level is achievable in the laboratory, doing so in the field is much more diffcult, which is well demonstrated by considering the magnitude of the perturbations in the proximity of a large structure as a specific example. This is an appropriate choice, because platform effects are a recurring problem for *in situ* optical methods. These perturbations are made more complex according to the sun orientation with respect to the structure, and differentially influence the data obtained by above-and in-water methods. For example, from the perspective of the in-water light field, investigations within 15–20 m of an offshore tower show significant effects of the structure: approximately 3–8% for clear-sky conditions, and as much as 20% under overcast conditions (Zibordi et al. 1999). Similar uncertainties have been estimated for in-water measurements from a ship (Voss et al. 1986).

From a measurement perspective, the above-water approach is more restrictive, because there is presently no reliable mechanism for floating an above-water system away from a platform (which is easily and effectively accomplished for an in-water system), so all above-water measurements are made in close proximity to a large structure. For the purposes of the results presented here, the proximity of the sampling platform is parameterized as the perpendicular distance x from the side of the sampling platform to the center of the area on the sea surface observed by the sea-viewing sensor, the so-called *surface spot*. The possible values of x range from approximately 0 (the field of view of the sensor must view only water and no part of the sampling platform), to a maximum value approximately equal to the height of the sensor above the water, H.

The team assembled to study platform perturbations imagined a horizontal deployment system (HDS) that would be easy to operate by one person, and modular for conventional transportation to the sampling platform. The idea wastobe able to extend an above-water system about 10 m away from the platform. The above-water instruments commonly in use are too large to safely use such a system on a moving platform, like a ship. The unique stability of a tower offered the best opportunity to satisfy all the design requirements, but only if the size of the radiometers could be significantly reduced. Prior to the initial design of the HDS, there was already a concerted effort to produce smaller and lighter sensors for SeaWiFS field campaigns. A next-generation (very small) version of the SeaWiFS Surface Acquisition System, called microSAS, was available for testing at the same time when the HDS design was being initiated, so this new sensor system was used to set the design criteria for the HDS (Hooker et al. 2003b).

The microSAS system measures the radiances required for the above-water approach used here, the so-called *modified Fresnel reflectance glint correction* as presented in the version 1 revision of the Protocols (Mueller and Austin 1995), hereafter referred to as S95. This method assumes the total radiance measured at the sea surface, $L_T(\lambda)$, is a combination of $L_W(\lambda)$ plus two sources of reflected light or *glint*: the sky and the sun. If the latter is minimized by pointing the measurement instruments at least 90◦ away from the sun plane (but not into any perturbations associated with the platform), the only quantity needed to retrieve $L_W(\lambda)$ from $L_T(\lambda)$isan estimate of the sky radiance, $L_i(\lambda)$, contribution. Removing the sky glint also requires an estimate of the surface reflectance, ρ.In the original formulation of S95, ρ wasa constant, but more realistic values for ρ as a function of the viewing geometry and the wind speed are available from Mobley (1999). The incorporation of the latter is hereafter referred to as the S01 method (Hooker et al. 2003b):

$$\hat{L}w_W^{S01}(\lambda) = L_T(\lambda) - \rho(W)L_i(\lambda), \tag{8.2}$$

where the pointing angles are omitted for brevity.

The tower-perturbation field measurements were carried out on the *Acqua Alta* Oceanographic Tower (AAOT) and within the framework of the Coastal Atmosphere and Sea Time Series (CoASTS) Project (Zibordi et al. 2002a). The tower is located in the northern Adriatic Sea approximately 15 km offshore of the Venice Lagoon in a frontal region that can be characterized by Case-1 or Case-2 conditions, although the former predominate (Berthon et al. 2002). The HDS was mounted on the topmost level (Fig. 8.2), and consists of a tubular horizontal mast sliding between rollers mounted within five rigid support frames. The HDS can carry an instrument package weighing approximately 10 kg, and to deploy it up to as much as 12 m away from the tower with a vertical deflection of the mast less than 1% (Van der Linde 2003). Although the HDS can be moved an arbitrary distance, 10 distance or *mast index* markers were placed on the horizontal mast in 1 m intervals. A mast index origin was established at the first mast support, so a quick determination of the relative position of the mast with respect to the tower could be determined (and reliably reproduced).

Following the work by Hooker and Morel (2003), the presence of an artificial perturbation in an above-water measurement can be detected (after wave effects have been removed) with the ratio

$$r(865) = \frac{L_T(865)/L_i(865)}{\rho(W)} \tag{8.3}$$

where the numerator comes from the Morel (1980) assumption that the sea surface is essentially *black* at a near-infrared wavelength (i.e., the above-water radiance measured is entirely due to surface reflection, principally from sky radiation once the sensor is pointed at least 90◦ away from the sun), and the denominator is the modeled surface reflectance from Mobley (1999). Under *natural* circumstances (i.e., in the absence of platform perturbations) and in Case-1 water conditions, $\rho(W) = L_T(865)/L_i(865)$, within the accepted variance, and $r(x, 865) = 1$. Any other reflected radiation added to the sky-reflected radiance leads to an increase in $L_T(x, 865)$, and $r(x, 865) > 1$.

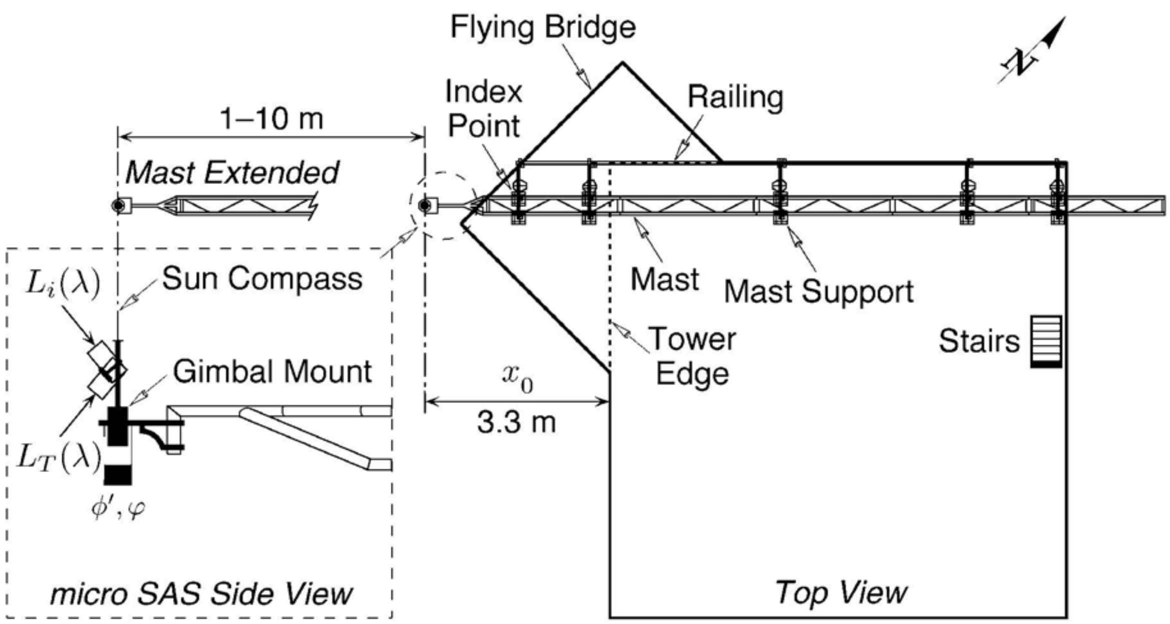

Fig. 8.2. Aschematic of the top view of the AAOT. The HDS is installed along the northwest edge and extends over the flying bridge that projects out over the main body of the tower. The microSAS sensors are mounted in a cardanic gimbal whose axes are aligned in the direction of, and perpendicular to, the HDS mast. Sensors inside the gimbal ballast confirm the azimuthal angle with respect to the solar azimuth, φ', is appropriate, and that the vertical (two-axis) tilt, φ, is less than 1^0. The latter confirms the nadir and zenith viewing angles (denoted υ hereafter) are correct. A complete experiment is made up of a set of approximately 10 microSAS measurement sequences, or casts. The casts are made at different mast index positions, m_i, which were sequentially set going from 1 to 10 or 10 to 1 (in 1 m increments).

The most important aspects of r (865) as an analytical variable are as follows:

1. It intrinsically includes the effects of changing solar illumination, because the sea-viewing observations are normalized by the sky radiance; and
2. It can be used to create a severity index, in the sense that the stronger the artificial increase in LT (x, 865), the larger the increase in r (x, 865), and the magnitude of the departure from unity (or an appropriate reference value) is an estimate of the severity of the contamination.

In Case-2 water conditions, or if the water type is close to the threshold of Case-1 and Case-2 conditions, r (x, 865) is not expected to be unity even far from the tower, so the last point requires some qualification: over the course of atower-perturbation experiment (usually requiring about 45 min), and in the absence of a source of artificial reflections, r (x, 865) is expected to remain essentially constant.
In other words, if the tower were not present, r (865) might not be unity, but it would remain constant over the time period of an experiment.

Departures from constancy (i.e., above the level of environmental variability) as a function of x are expected to be an indicator of the presence of platform perturbations, particular if they show a significant increase as x decreaess. The constancy of r (865) can be quantified by selecting one of the most distant far-field observations within an experiment as a reference point, x. The RPD, ψ, is again used to quantify the di□erence between an observation Y with respect to a reference value X. For the specific case of determining changes in r (865) as a function of x, the RPD (1) is computed as

$$\varphi(x) = 100\frac{r(x,865) - r(x^1,865)}{r(x^1,865)} \tag{8.4}$$

where x^1 is the reference point in the calculation and $\psi(x)$, the RPD value, is the so-called severity index.

An ensemble description of the perturbation field, in terms of the severity index, can be created by binning the RPD data as a function of x and averaging the values in each bin. Scaling the x values by the height of the sensor above the water (also approximating the height of the tower), H, permits a more generalized description of the data. The result of this process is shown in Fig. 8.3, along with delineations of the original minimum and maximum extents of the RPD values. The intersection of the perturbation curves with the scaled surface spot distance (x/H) gives the minimum, (expected) average, and maximum severity indexes. The curves show three important aspects of the tower-perturbation field:

1. The maximum perturbations occur very close to the tower (small values of x/H);
2. As x/H increases and approaches 1 (i.e., as the surface spot becomes as far away as the platform is high), the platform perturbation curves converge towards smaller and smaller values; and
3. For $x>H$, the platform perturbation is negligible.

It is important to remember the perturbation here is modeled only in terms of the severity index. The azimuthal-viewing arcs in Fig. 3 (based on $\upsilon = 40^\circ$) allow the RPD curves to be used to predict the severity index for a particular azimuthal-viewing angle. Conversely, the data in Fig. 8.3 can be used to determine what maximum azimuthal-viewing angle can be used while maintaining a certain severity index. For example, for a severity index of 3%, an instrument mounted on the edge of a platform (x_0 =0.0m) can be azimuthally rotated up to $\pm$ 23.1^0 (α is assumed symmetrical), and an instrument displaced
3.3 m from the edge of the platform can be rotated up to $\pm$ 51.6^0.

A topic deserving additional consideration is the spectral aspects of the tower perturbation in the near field. It is important to remember that the severity index is only a relative diagnostic and cannot be used as an absolute predictor. The primary reason why a severity index versus spectral radiance approach will yield a different description of the tower perturbation is the geometry at the time of sampling, both in terms of the sun and the mechanical pointing of the instruments. The geometry controls the importance of platform shading versus superstructure reflections, and the resulting net perturbation from these contamination effects is strongly spectrally dependent.

Alternative spectral analyses for the tower perturbation investigation based on above-water normalized water-leaving radiances are presented by Hooker and Zibordi (2003b). These analyses confirm the generalized metric established with the original work by Hooker and Morel (2003): the primary avoidance principal for a sea-viewing sensor mounted on the illuminated side of a platform is that it must be pointed to a spot on the sea surface that is at least as far away as the platform is high. The successful application of the generalized sampling metrics established here to an automated above-water sampling system is presented by Zibordi et al. (2003c).

It is important to remember this study was based on a simplistic and symmetric (box-like) structure. It is likely that some of the results will not be immediately applicable to asymmetric or highly reflective platforms, and some extra considerations will have to be applied. For example, a sensor mounted on the bow of a ship, with the main superstructure set far back from the bow, will probably have to view a surface spot that is as far away as the height of the bow railing. Ships with superstructures set much closer to the bow, especially those painted white, will probably require a surface viewing distance that approximates the full height of the superstructure.

In any case, each platform is a particular case, and each instrument mounting location a separate challenge. Although this study can provide guidance, it cannot answer all questions for all platforms. The most important lesson is that a perturbation analysis needs to be conducted for each above-water instrument location to determine the level of contamination as a function of the pointing parameters. For calibration and validation activities, sampling of the unperturbed far field will be a necessity that might not be easily satisfied without specially-designed mounting hardware.

8.4 DATA PROCESSING PROTOCOLS

Although above-water determinations of water-leaving radiances are part of the databases used to create global bio-optical models, the majority of the data for these activities are from in-water measurements (O'Reilly et al. 2000). Part of this disparity is historical, in-water measurements have been conducted for a longer time period, and part of it is the consequence of the poor agreement that is frequently obtained when the two methods are intercompared (Rhea and Davis 1997, Fougnie et al. 1999, Toole et al. 2000, and Hooker et al. 2002a), so traditional in-water measurements have been preferred.

Aportion of the discrepancy between the two methods was recently shown to be caused by wave effects (Hooker et al. 2002a and Zibordi et al. 2002b), platform perturbations (Hooker and Morel 2003 and Hooker and Zibordi 2003b), and the anisotropy of the upwelled radiance field (Morel and Gentili 1996). The latter is particularly important, because in-water systems are usually nadir viewing, whereas above-water systems are not). The study presented here builds on these accomplishments by analyzing simultaneous above-and in-water optical observations, wherein one of the two measurements was unequivocally free of platform perturbations, and implementing an above-water method with corrections for many problems unique to above-water methods. This data set is then used for the following objectives, which are examined within the generalized requirements of calibration and validation activities (i.e., the generalized 1% radiometry needed to satisfy the SeaWiFS absolute uncertainty requirement): a) evaluate the capabilities of above-water radiometry in shallow, coastal waters; and b) determine if the above-and in-water methods converge to within the uncertainties associated with the two methods.

For a meaningful comparison with the (nadir-viewing) in-water sensors, the above-water methodology needs to be corrected to account for the bidirectional dependency of the upward radiance field below the surface with that exiting the surface. The basic equations for this transformation (Morel and Gentili 1996 and Mobley 1999) are an established part of the Protocols (Morel and Mueller 2002) and have been successfully incorporated into above-water measurements (Hooker and Morel 2003, Hooker and Zibordi 2003b, and Hooker et al. 2003c), so only only a brief summary is presented here.

The radiance bidirectionality is parameterized by the so-called Q-factor, which takes a particular value, denoted Q_n, for the nadir-viewing measurements. For above-water measurements, the angular parameters are imposed by the pointing angles of the sensors, as well as the surface effects of reflection and refraction. When dealing exclusively with Case-1 waters, the functional dependence of the variables can be simplified. In particular, it is assumed that the inherent optical properties are universally related to the chlorophyll *a* concentration (Morel and Prieur 1977), *Ca*.

Because a nadir-transformed, above-water estimate of L_W is equivalent to the in-water value, a formulation can be produced (Morel and Mueller 2002) to correct the S01 method, and is hereafter referred to as the Q02 method:

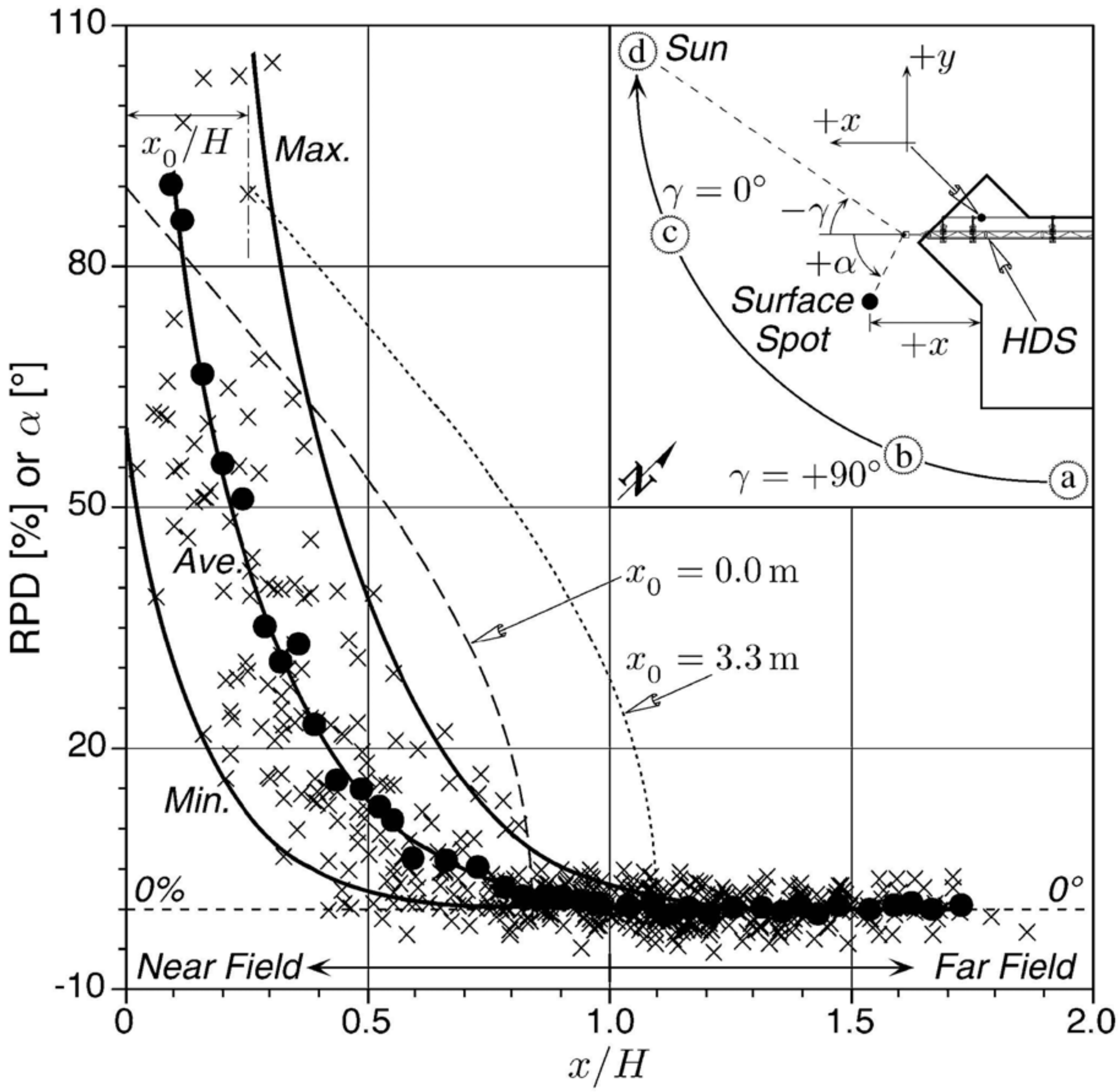

Fig. 8.3. The bin-averaged r (865) RPD values (solid circles and associated curve) as a function of x/H. Also shown are the curves delineating the minimum and maximum RPD values associated with the full data set (the x symbols). Superimposed on these curves are the azimuthal-viewing arcs based on υ =40◦ for a sensor mounted on the edge of a platform (x_0 =0.0m) and one mounted at mi =1 (the first mast index position) on the HDS (x_0 =3.3 m). Each viewing arc gives the scaled distance to the surface spot (x/H) asa function of α. The x_0 =3.3m arc ends at x_0 /H =0.25 (α =90◦), although, lower x/H values could be measured. The inset panel shows a schematic of the localized (x,y) coordinate system, along with the geometry for the pointing angles with respect to the sun (γ) and the surface spot viewed by the sea-viewing sensor (α). Note the origin of the localized coordinate system (denoted by the intersection of the +x and +y axes) is a point at the northwest corner of the tower within the area associated with the flying bridge.

$$\hat{L}_W^{Q02}(\lambda) = \frac{\Re_0}{\Re(\theta^1, W)} \frac{Q(\lambda,\theta,\phi^1,C_a)}{Q_n(\lambda,\theta,C_a)} \hat{L}1(\lambda) \qquad (8.5)$$

where the Q terms are evaluated at null depth (z =0$^-$), θ is the solar zenith angle, θ' is the above-water viewing angle (υ) refracted by the air–sea interface, and the factor merges all the effects of reflection and refraction (the 0 term is evaluated at nadir, i.e., $\theta = 0$). All the correction terms are computed here from look-up tables (Morel et al. 2002). An above-water instrument system cannot be floated away from a sampling platform, but this is easily and effectively accomplished with many in-water profiler designs. Within the context of this generalized difference between the two methods, an above-water acquisition effort—even if platform perturbations are recognized and minimized—is still more likely to contain platform-contaminated acquisition sequences than profiles from a simultaneous in-water method. There are exceptions to this generality, but it remains more true than not, and is one of the reasons why in-water calibration and validation exercises predominate. Using these arguments as an overall rationale for prioritizing the data used in this study, the analytical perspective adopted here is as follows:

1. Use the in-water observations as the reference measurement for evaluation purposes.
2. When matching the above-and in-water observations, use only simultaneous or nearly simultaneous (within ± 5 min) data acquisition sequences to minimize environmental influence.
3. Use radiometers with absolute calibrations from separate calibration facilities (the usual case for most investigators), but intercalibrate the sensors to quantify the effect of eliminating differences in the calibration standards and procedures.

Although the discussion contained within the aforementioned rationale readily supports a decision to use the in-water measurements as the analytical reference, another reason for doing so is the in-water data processor used here has been evaluated in a data processor round robin and its uncertainties are well quantified (Hooker et al. 2001).

An intercomparison of the intercalibrated above-and in-water methods, for all the Case-1 and Case-2 data (Loisel and Morel 1998) is presented in Fig. 8.4. With the exception of a small number of values at 555 nm, the majority of the data are well distributed around the 1:1 line, although the lower edge of the variance is defined by a large number of the values at 510 nm. The AAOT above-water measurements were unequivocally free of platform perturbations, whereas for the ADRIA-2000 data, the in-water observations were free of perturbations. Because the Fig. 8.4 data do not show any significant biases, platform perturbations were properly avoided, and the Case-2 data are not substantially different from the Case-1 data. The average RPD of all the intercalibrated data is approximately 1.8%, and if the independently calibrated data are considered, the average RPD increases to about 2.3%. In either case, the average RPD values are to within the uncertainties associated with the absolute calibration of the radiometers (Hooker et al. 2002b). Additional details on the total uncertainty budget of both methods are presented by Hooker et al. (2003c).

An interesting aspect of the Fig. 8.4 results is the very good agreement for the overcast data (much of the data at approximately 0.3 $\mu\mathrm{W cm^{-2}\,nm^{-2}\,sr^{-1}}$ and below are from overcast stations). This is an added capabilitiy of the above-water method used here, and shows an enhanced flexibility of the method. It can be particularly important in some circumstances, because cloud conditions are not predetermined by any means, and many field expeditions get only limited opportunities to sample certain regimes.

The importance of properly accounting for bidirectional effects and accurately determining the surface reflectance is demonstrated by replacing (λ) with $\hat{L}_W^{Q02}(\lambda)$ with $\hat{L}_W^{S95}(\lambda)$ in the intercomparisons of the intercalibrated results (the S95 method assumes ρ =0.028 and there is no Q-factor correction). The results of this substitution is a significant bias—almost all the data are above the 1:1 line—that is, the S95 method overestimates the water-leaving radiances across all bands. The average magnitude of the overestimation is approximately 6.6%, which is about 4.8% above the Q02 intercalibrated results. This level of difference is in keeping with the differences in above-and in-water methods documented by Hooker et al. (2002a), wherein the former were not bidirectionally corrected.

The SeaWiFS uncertainty requirements were based primarily on an open ocean perspective. The data presented here were collected in the coastal environment, so the level of agreement that has been achieved is significantly better than originally anticipated. The convergence of the Q02 above-water method with the traditional in-water technique was primarily the result of careful metrology, platform perturbation avoidance, state-of-the-art corrections to the primary variables, plus comprehensive and independent evaluations of the calibration and data processing schemes. If this level of effort is reproduced in similar or simpler environments (coastal waters predominated by Case-1 conditions or the open ocean), there is every reason to believe that the Q02 above-water method can be used at the same level of effcacy as an in-water method. Furthermore, this should be equally true both for calibration and validation activities and bio-optical modeling requirements.

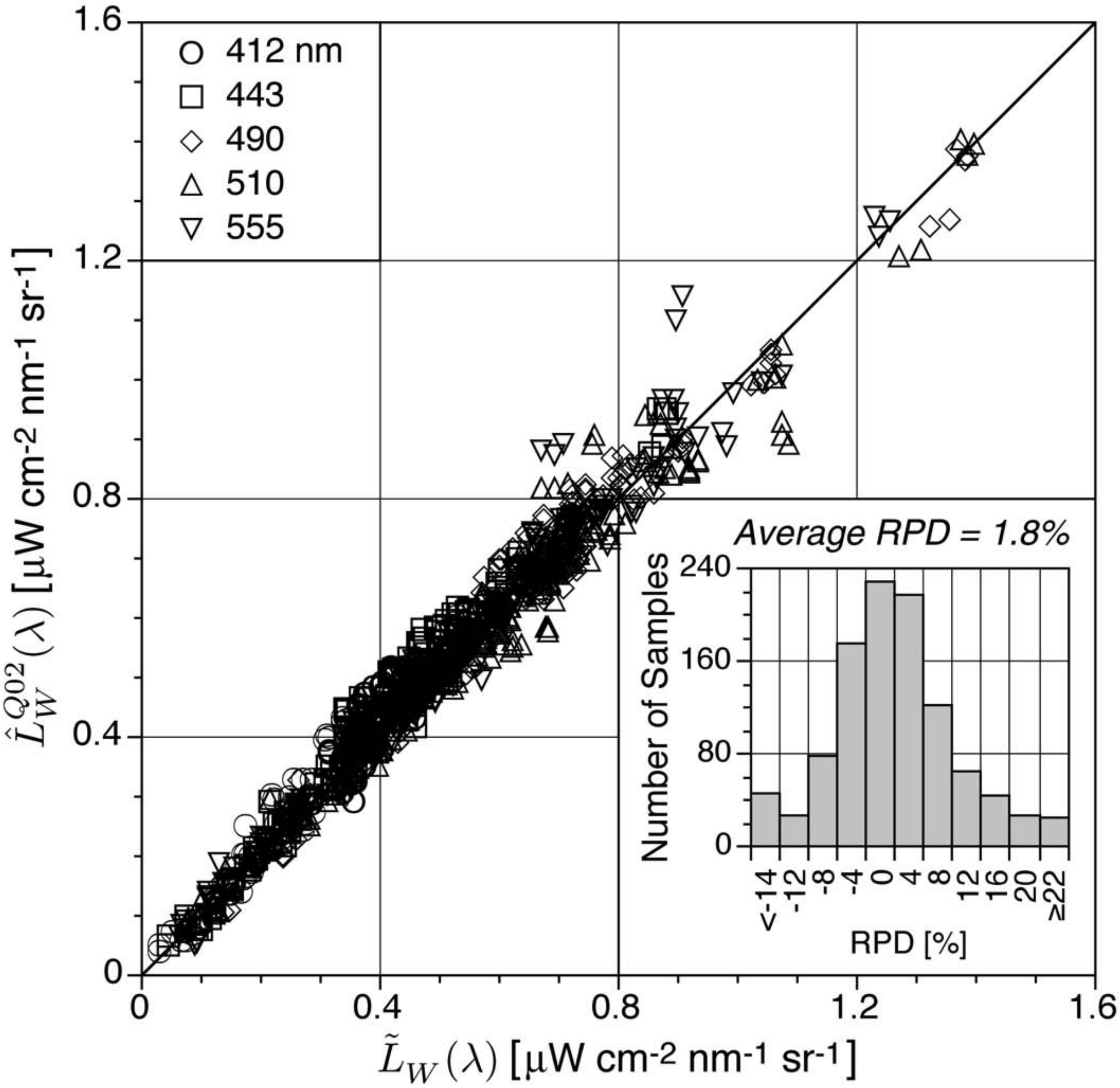

Fig. 8.4. An intercomparison of intercalibrated (Q-corrected) above-water determinations of water-leaving radiances, $\hat{L}_W^{Q02}(\lambda)$, with simultaneous in-water determinations, $\tilde{L}_W(\lambda)$, for Case-1 and Case-2 conditions. The data were collected at the AAOT under sampling geometries that avoided all platform perturbations and during the Adriatic Data collection for Research on marine Inherent and Apparent optical properties field campaign (conducted in 2000 and referred to hereafter as ADRIA-2000). The majority of the data are for Case-1 conditions (about 85%), and the Case-2 stations were close to the threshold between the two water typesas defined by Loisel and Morel (1998). The vast majority of all optical data were collected under clear-sky conditions, and the average environmental conditions were excellent: cloud cover was less than 2/10, wind speed was less than 5 m s^{-1}, and wave height was 0.3 m or less. Water depth at the AAOT is 17 m, wheras it ranged from 7.4–32.3 m during ADRIA-2000.

8.6 DATA ARCHIVE

The SIRREX-8 activity established that the immersion factors originally supplied with the SeaWiFS Field Team profiling equipment were significantly incorrect (by more than 10% in the blue part of the spectrum). Consequently, the entire archive of *in situ* optical measurements are being reprocessed. This activity has been coordinated with the production of a new optical data processor, so many of the data processing protocols that were refined during the investigations for the SIMBIOS project could be utilized. The reprocessing is in the final stages of quality assurance, and a preliminary assessment indicates a substantial improvement in many of the primary and bio-optical variables. A final set of water-leaving radiances and ancillary parameters for those campaigns that were not specialized experiments (like the tower perturbation investigations) will be delivered to the SeaWiFS Bio-Optical Archive and Storage System (SeaBASS) before the end of 2003.

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